Plant and Soil Science

Journal homepage: https://agriculturalscience.com.ua/en
Plant and Soil Science, 15(3), 68-80
Received: 11.04.2024 Revised: 09.07.2024 Accepted: 15.08.2024

UDC 631.164.04(477.292.485)
DOI: 10.31548/plant3.2024.68

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The effectiveness of intercropping in the Forest-Steppe zone of Ukraine

Abstract. Intercropping of agricultural crops offers a valuable technological solution for resource conservation and improved crop yield, essential to global food security. This study aimed to assess the effectiveness of intercropping maize and soybeans. Scientific methods were employed for conducting field and laboratory research, with experimental findings analysed statistically and interpreted. The study established that intercropping maize variety RAGT Zanetikks with soybean varieties Sirelia and Sakuza provides several advantages over monoculture cropping, especially in terms of yield formation. Maize demonstrated efficient utilisation of additional soil nitrogen fixed by soybeans in mixed plantings, resulting in significant maize yield gains across all fertiliser levels and even without fertilisation. The increase in maize yield in intercropped systems, compared with monoculture, ranged from 10.3% to 19.3%, depending on the fertiliser rate. The highest maize yield was achieved with $N_{90}P_{60}K_{60}$ fertilisation: 10.26 t/ha in monoculture and 12.19-12.24 t/ha in intercropped systems. Although soybean yield declined in intercropped plantings, the combined yield of both crops in intercropping systems showed a substantial increase, reaching 14.51-14.70 t/ha under $N_{90}P_{60}K_{60}$ conditions. The yield was strongly correlated with the leaf area index (r = 0.93-0.99). Soil nitrate nitrogen content was higher under soybean but decreased under intercropping systems.

Suggested Citation:

Mokrienko, V., Kalenska, S., & Andriec, D. (2024). The effectiveness of intercropping in the Forest-Steppe zone of Ukraine. *Plant and Soil Science,* 15(3), 68-80. doi: 10.31548/plant3.2024.68.

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Soil biological activity increased with $N_{60}P_{45}K_{45}$ fertilisation in maize and soybean monocultures (39.4 and 47.2 mg CO_2/kg soil/day, respectively) and reached 52.6-55.1 mg CO_2/kg soil/day in intercropped plantings. These findings have significant practical implications for production, promoting resource conservation and increasing gross grain production

Keywords: leaf area index; photosynthetic potential; soil biological activity; soil nitrate nitrogen content; yield

INTRODUCTION

The efficient use and conservation of natural resources, coupled with the optimisation of technological inputs in crop production within the Forest-Steppe zone of Ukraine, has become increasingly pressing given the need to bolster food production. Intercropping, a method that combines different crops within the same planting space, has the potential to significantly enhance the efficiency of land use and reduce the need for additional inputs aimed at boosting yields. This approach contributes to a decrease in the use of fertilisers and pesticides, mitigating negative impacts on soil and water, and also helps to reduce greenhouse gas emissions associated with conventional agricultural practices. P. Manasa *et al.* (2020), through a comprehensive analysis of yield structure, productivity, competitiveness, and economic efficiency of intercropping maize with legumes, demonstrated the high effectiveness of such plantings. E.S. Jensen *et al.* (2020) indicated that the share of intercropping in European agriculture is increasing to develop more sustainable agriculture and create efficient food production systems.

E. Gillbard (2022) demonstrated that, for intercropping systems, the mechanism for increasing yield is primarily focused on nutrient optimisation. A. Wysokiński & B. Kuziemska (2019) dedicated their research to the shared use of resources and the increased proportion of fixed nitrogen through transport from the legume crop to the partner crop. W. Wang *et al.* (2022) proved that intercropping soybean with cereals demonstrates a positive interaction, significantly increasing the productivity of maize and wheat by 18.1-20.9%. The authors showed that biomass accumulation increased in intercrops: in monoculture systems, the average above-ground biomass of corn was 22.9 t/ha, soybean – 8.1 t/ha, and wheat – 11.8 t/ha; in intercrops, biomass increased by 14.5 and 17.9%, and the maximum instantaneous growth rate of corn and wheat increased by 29.4 and 34.0%, respectively. As indicated by S. Maitra *et al.* (2020), the system of intercropping was widely used in semi-arid regions due to its high and stable productivity, and efficient resource use.

In Ukraine, research on intercropping systems for forage production has been ongoing for an extended period. The results obtained by V.I. Dudchenko (2017) confirmed the effectiveness of optimal species selection, which contributes to increased vegetative mass formation and dry matter accumulation. In connection with the growing demand for biofuels, research has emerged on the intercropping of energy crops with partner crops to effectively utilise wide row spacing and produce additional plant products. Such studies have been conducted on the selection of combinations of energy crops with other species. V.O. Dekovets & M.I. Kulyk (2023) showed that the highest biomass yield of miscanthus is formed when intercropped with lupin and using the mycorrhizal preparation Mycofriend to feed energy crops – 20.7 t/ha. At the same time, research on intercropping cereal and legume crops grown for grain production in Ukraine is only beginning and requires unconditional expansion. A. Shuvar *et al.* (2019) studied the formation of productivity of agrocenoses of spring cereals and legumes when grown on the sloping lands of the Carpathian region. It was established that when sowing mixtures of cereals and legumes, yield indicators increased compared to monocultures and depended on the fertiliser background.

The study aimed to establish the effectiveness of intercropping maize and soybeans in terms of increasing total crop production, enhancing nitrogen utilisation, improving soil biological activity, and optimising the functionality of the crops' photosynthetic surface.

The research objectives were to: assess the impact of intercropping maize and soybeans on gross agricultural production; investigate nitrogen utilisation efficiency and soil biological activity under intercropped maize and soybean conditions; and substantiate the specific features of photosynthetic surface function in intercropped systems, aiming to develop agrocenoses with greater resilience to stress conditions.

MATERIALS AND METHODS

The research was conducted in the educational and scientific laboratory of the Department of Crop Growing at a separate subdivision of the National University of Life and Environmental Sciences of Ukraine (NULES) "Agronomic Research Station" (Pshenychne village, Kyiv Region) on typical low-humus chernozems in 2022-2024. Laboratory analyses were carried out in the "Analytical Studies in Crop Production" laboratory, also part of the Department of Crop Growing at NULES. The experiments were set up following standard methodologies for field research (Rozhkov, 2016). The field experiment employed a split-plot design with two factors. First-order blocks were allocated to field crops, including both monoculture and intercropped plantings, while second-order blocks focused on fertilisation treatments. Each plot measured 100 m^2, with a net harvested area of 80 m^2. The experiment included four replications.

The planting scheme and seeding rate for each crop were aligned with the experimental design (Table 1). In monoculture, the seeding rate for soybeans and maize corresponded to the zonal recommendations of the originator. In intercrops, the seeding rate for soybeans was reduced by 50%. The sowing depth for maize was 4-5 cm, and for soybeans, 2-3 cm.

Table 1. Experimental design: Factor A – monocultures and intercrops

No.	Crop/Intercrop, *Factor A*	Variety/Hybrid	FAO/CHU	Seeding rate (thousands of seeds)
1	Maize	RAGT Zanetikks	FAO 340	70
2	Soybean	Sirelia	CHU 2300	450
3	Soybean	Sakuza	CHU 2600	450
4		RAGT Zanetikks + Sirelia		70 thousand/ha+225
5		RAGT Zanetikks + Sakuza		70 thousand/ha+225

Source: compiled by the authors

Factor B – *fertilisation, kg/ha of active substance (a.s.):*

1. No fertilisation – control (C)
2. $N_{60}P_{45}K_{45}$.
3. $N_{90}P_{60}K_{60}$.

Sowing methods: monocultures – maize with a row spacing of 70 cm, soybeans – 19 cm; intercrops – maize 70 cm, with one row of soybeans sown between the rows. All crops were sown at the same time. Sowing was carried out using seed drills with press wheels – specifically, Kinze and Great Plains.

During the experimental research, the following observations and measurements were conducted, following the methodologies outlined by A.O. Rozhkov (2016):

- *Phenological observations* recorded dates for emergence, duration from emergence to flowering, and from flowering to full grain maturity. Plant counts were conducted on two-metre sections of rows at 2 to 4 evenly spaced points along the diagonal lines of each plot. The initial seedling phase was recorded when 15% of plants had emerged in the plot, and full emergence when 75% of plants had emerged, with rows clearly visible across the plot.
- *Linear measurements* – during the tasselling phase of maize, the leaf area of the plants' assimilation apparatus was measured in both monoculture and intercropped plantings.

Leaf area was determined using the "cutting" method:

$$S = (M*n*k)/m, \quad (1)$$

where M is the mass of leaves in the sample, g; n is the area of one cutting, cm^2; k is the number of cuttings, pcs; m is the mass of cuttings, g.

- *Photosynthetic activity of maize crops* measured as the photosynthetic potential (PP). The photosynthetic potential of the crop (PP) is calculated as the product of the average leaf assimilation area (S_L) and the duration of the active growing period (tGRW):

$$PP = S_L * tGRW, \ m^2 \cdot days/ha. \quad (2)$$

In maize, 1000 units of PP provide for the formation of 3-5 kg of grain, and in soybeans, 0.81.5 kg of seeds.

- *Nitrate nitrogen content in the soil* was determined using a photometric method with disulphophenolic acid according to DSTU 4729:2007 (2007). This method is based on the ability of nitrates to react with this acid to form trinitrophenol, which in an alkaline medium forms yellow ammonium trinitrophenolate. The intensity of the colour is proportional to the nitrogen content. Photometric analysis of the solution was performed to determine the nitrate content.
- *CO_2 emission intensity per 1 m² per hour* was determined using the method developed by V.I. Shtatnov.
- *Biological grain yield of maize* – as maize has a high pre-harvest grain moisture content, the yield was recalculated to dry grain using the formula (3):

$$Y = Ym \cdot (100 - m)/(100 - Sm), \text{ centner/ha}, \quad (3)$$

where Y is the grain yield at standard moisture, centner/ha; Ym is the grain yield at actual moisture, centner/ha; m is the actual moisture content of the grain (at harvest), %; Sm is the standard moisture content, %.

- *Biological seed yield of soybeans* – the number of plants per 1 m^2 was determined in several locations within the field. Plants were counted in 4-8 adjacent rows, ensuring that the total area, including row spacing, measured 1 m^2. The biological yield was calculated using the formula (4):

$$Y = N \cdot P \cdot S \cdot W/10^5, \quad (4)$$

where N is the number of plants per 1 m^2; P is the average number of developed pods per plant, pcs; S is the average number of seeds per pod, pcs; W is the 1,000-grain weight, g.

- *Agricultural techniques for field research* – maize seed was treated with a fungicideinsecticide complex, specifically Maxim XL (1.0 L/ton) + Poncho (2.7 L/ton). Soybean seed was treated with the fungicide Standak Top (10 L/ton) and the inoculant HiCoat (1.4 L/ton) – an inoculant in liquid formulation with an extender (*Bradyrhizobium japonicum* bacteria, strain 532C).

The research was conducted following the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992). Winter wheat was the preceding crop in the experiment. The wheat grain yield was 6.2 t/ha, and accordingly, 7.8 t/ha of by-products were returned to the soil. Soil cultivation involved stubble harrowing at a depth of 10-12 cm and ploughing at a depth of 25-27 cm. According to the experimental design and the mineralisation of plant residues, FERTIS NPK (10-20-20+S+ME) fertiliser was applied before primary tillage, and the remaining nitrogen fertilisers in the form of ammonium nitrate (34.4%) were applied during pre-sowing cultivation. At the stage of physical maturity of the soil, early spring moisture conservation was carried out. Two weeks later, cultivation was performed, and pre-sowing cultivation was carried out when the soil was consistently warmed to a depth of 10 cm to +10°C.

Before pre-sowing cultivation, the soil herbicide Primextra TZ Gold (4.5 L/ha) was applied. At the 3-5 leaf stage of maize, which coincided with the 1-3 trifoliate leaf stage of soybeans, the rescue herbicide Bazagran (3.0 L/ha) + surfactant Metolat (1.0 L/ha) was applied. The spray volume was 200 L/ha.

Harvesting and determination of biological yield were carried out at full maturity of the crops using modern methods – based on yield components recalculated to a basic moisture content of maize 14% and soybeans 12%.

RESULTS

Maize and soybeans are leading crops in Ukraine in terms of production. Innovative approaches to growing maize and soybeans are taking their production to a new level of economic, agricultural, and environmental efficiency. Intercropping of legumes and cereals has several advantages for partner crops, but at the same time, several questions require further research. Intercropping alters the cenoctic relationships in agrocenoses compared to monocultures of similar hybrids and varieties, which is reflected in various biological and morphological development traits of the crops and the formation of their productivity (Feng *et al*., 2020).

The phenology of growth and development in plants within intercropped and monoculture agrocenoses differs significantly and is also heavily influenced by fertiliser rates (Table 2).

Table 2. Duration of the growing season for monoculture and intercropped maize and soybeans, in days, average for 2022-2024

Hybrid + Variety	Fertilisation, kg/ha a.s					
	No fertiliser (control)		$N_{60}P_{45}K_{45}$		$N_{90}P_{60}K_{60}$	
	Duration of growing season, days					
	M	S	M	S	M	S
RAGT Zanetikks, control	115	–	118		122	–
Sirelia	–	95	–	98	–	106
Sakuza	–	105	–	110	–	118
RAGT Zanetikks + Sirelia	117	98	121	103	125	114
RAGT Zanetikks + Sakuza	117	110	122	114	127	124

Note: M – maize, S – soybean, a.s. – active substance
Source: compiled by the authors

The duration of the growing season in both monoculture and intercropped plantings increases with higher rates of mineral fertilisers. In monoculture maize crops, an increase in fertiliser rates leads to a 3-7-day extension of the growing period, while in intercropped systems, the duration is extended by 4-8 days. However, the extension of the maize growing period in intercropped systems under similar fertilisation regimes is only 2-3 days. The extension of the growing season for soybean varieties in monoculture, with increased fertiliser rates, ranged from 3 to 13 days depending on the fertiliser rate and soybean variety, while in intercropped systems, the extension was 3-8 days, again depending on the fertilisation background and variety.

Intercropping maize with legumes, in contrast to monoculture planting, makes more efficient use of natural resources, particularly light. This is because the stems and leaves of the cereal and legume plants are arranged in different layers, allowing for more effective utilisation of solar energy. The intensification of photosynthesis presents new opportunities for increasing yield.

The productivity of photosynthesis in a crop is determined by two main factors: the total leaf surface area and the intensity of photosynthetic processes per unit of leaf area. The stratification of maize and soybean plants in mixed plantings led to differences in the formation of the assimilatory surface area, compared to monoculture plantings (Table 3).

Table 3. Leaf surface area of monoculture and intercropped plantings, in the tasselling phase, thousand m2/ha, 2022-2024

Hybrid + Variety	Leaf surface area*, thousand m^2/ha								
	M	S	M+S	M	S	M+S	M	S	M+S
	Fertilisation, kg/ha a.s								
	No fertiliser (c)			$N_{60}P_{45}K_{45}$			$N_{90}P_{60}K_{60}$		
RAGT Zanetikks, (c)	37.2	–	37.2	42.1	–	42.1	44.4		44.4
Sirelia	–	32.1	32.1	–	34.2	34.2	–	36.7	36.7
Sakuza	–	32.9	32.9	–	35.4	35.4	–	37.2	37.2
RAGT Zanetikks + Sirelia	35.4	19.5	54.9	38.6	20.8	59.6	41.2	22.2	63.4

Table 3, Continued

Hybrid + Variety	Leaf surface area*, thousand m^2/ha								
	M	S	M+S	M	S	M+S	M	S	M+S
	Fertilisation, kg/ha a.s								
	No fertiliser (c)			$N_{60}P_{45}K_{45}$			$N_{90}P_{60}K_{60}$		
RAGT Zanetikks + Sakuza	35.2	21.3	56.5	41.1	22.0	63.1	42.7	23.1	65.8
Correlation coefficient** (r)	0.99	0.97	0.93	0.99	0.97	0.96	0.99	0.94	0.95

Note: * – M – maize; S – soybean; M+S – maize and soybean together; ** – correlation coefficient for "leaf surface area" and "yield", a.s. – active substance, c – control
Source: compiled by the authors

In monoculture plantings, the leaf surface area of individual crops was greater than in intercropped systems, specifically 37.2-44.4 thousand m^2/ha for maize and 32.1-37.2 thousand m^2/ha for soybean, increasing with higher fertiliser rates. At the same time, intercropping maize and soybean together resulted in a larger total leaf surface area – in the combination of Zanetikks + Sirelia – 54.963.4 thousand m^2/ha; Zanetikks + Sakuza – 56.5-65.8 thousand m^2/ha.

The photosynthetic potential of the crop (PP) more fully characterises the photosynthetic activity of field crop plantings, reflecting the efficiency of the leaf apparatus over the period during which the assimilatory apparatus remains physiologically active (Table 4).

Table 4. The photosynthetic potential of monoculture and intercropped maize and soybean, million m^{2*}days/ha, 2022-2024

Hybrid + Variety	Leaf surface area, thousand m^2/ha								
	M	S	M+S	M	S	M+S	M	S	M+S
	Fertilisation, kg/ha a.s								
	No fertiliser (c)			$N_{60}P_{45}K_{45}$			$N_{90}P_{60}K_{60}$		
RAGT Zanetikks, (c)	2.34	–	2.34	2.71	–	2.71	2.96	–	2.96
Sirelia	–	1.67	1.67	–	1.83	1.83	–	2.13	2.13
Sakuza	–	1.89	1.89	–	2.13	2.13		2.40	2.40
RAGT Zanetikks + Sirelia	2.26	1.05	3.31	2.55	1.17	3.72	2.81	1.38	4.19
RAGT Zanetikks + Sakuza	2.25	1.28	3.53	2.75	1.37	4.12	2.96	1.56	4.52

Note: M – maize; S – soybean; M+S – maize and soybean together, a.s. – active substance, c – control
Source: compiled by the authors

Providing plants with essential nutrients is a crucial component in the formation of yield and grain quality. Adequate nitrogen levels in the soil ensure proper growth and development of plants, making it one of the key indicators of soil fertility. Nitrogen in its nitrate form is easily absorbed by plants, and thus this indicator reflects the soil's mineral nitrogen content. In mixed crops, with a specific ratio of components, maize is the primary consumer of nitrogen (Table 5).

Table 5. Nitrate nitrogen (NO_3) content in the 0-30 cm soil layer, at the 9-10 leaf stage of maize, mg/kg of soil, 2022-2024

Hybrid + Variety	Fertilisation, kg/ha a.s		
	No fertiliser	$N_{60}P_{45}K_{45}$	$N_{90}P_{60}K_{60}$
RAGT Zanetikks, control	12.1	13.5	13.7
Sirelia	14.5	15.1	15.6
Sakuza	14.2	15.3	15.8
RAGT Zanetikks + Sirelia	13.5	14.7	15.0
RAGT Zanetikks + Sakuza	13.6	14.5	14.8

Note: a.s. – active substance
Source: compiled by the authors

The nitrate nitrogen content in the soil varied depending on whether monoculture or mixed crop cultivation was used, as well as the fertilisation practices. The highest nitrate nitrogen content in the soil at the 9-10 leaf stage of maize was observed in monoculture soybean cultivation, ranging from 14.2 to 15.8 mg/kg of soil. According to the grading system, this level is considered high. Maize has two critical periods concerning the uptake of mineral nutrients. The first, which coincides with the phase between seedling emergence and the 5-7 leaf stage, is critical for phosphorus nutrition. The second critical period is during the period of intensive growth and development (9-10 leaf stage to tasselling), during which maize plants consume approximately 70% of their total nitrogen, thus influencing the soil's nitrate nitrogen reserves (Table 6).

Table 6. Nitrate nitrogen (NO_3) content in the 0-30 cm soil layer at the tasselling stage of maize, mg/kg of soil, 2022-2024

Hybrid + Variety	Fertilisation, kg/ha a.s		
	No fertiliser (c)	$N_{60}P_{45}K_{45}$	$N_{90}P_{60}K_{60}$
RAGT Zanetikks, control	10.4	12.9	13.2
Sirelia	14.2	14.8	15.3
Sakuza	14.4	14.9	15.5
RAGT Zanetikks + Sirelia	12.1	13.4	14.1
RAGT Zanetikks + Sakuza	12.1	13.2	14.2

Note: a.s. – active substance
Source: compiled by the authors

At the tasselling stage of maize, the highest levels of nitrate nitrogen reserves were recorded in monoculture soybean crops. In mixed crops, the nitrate nitrogen content was lower, which is attributed to the significant nitrogen absorption by the maize plants. With the application of $N_{90}P_{60}K_{60}$, the nitrate nitrogen content in the mixed crop of RAGT Zanetikks + Sakuza was 14.2 mg/kg of soil, indicating a high level of nitrogen availability. Research into soil biological activity provides a broader understanding and reveals patterns in the processes of organic matter transformation, taking into account the anthropogenic impact on the soil and its properties (Table 7).

Table 7. Total biological activity of the soil, mg CO_2/kg soil/day, 2022-2024

Hybrid + Variety	Fertilisation, kg/ha a.s		
	No fertiliser (c)	$N_{60}P_{45}K_{45}$	$N_{90}P_{60}K_{60}$
RAGT Zanetikks, control	33.1	39.4	37.4
Sirelia	44.6	47.2	43.2
Sakuza	44.6	47.5	42.8
RAGT Zanetikks + Sirelia	40.6	52.6	50.5
RAGT Zanetikks + Sakuza	42.5	55.1	51.3

Note: a.s. – active substance
Source: compiled by the authors

Observations of soil respiration intensity over time revealed that the highest values of this indicator occurred in the middle and latter stages of the growing season, while the lowest values were observed at the beginning. A positive effect of the interaction between maize and soybean in intercropping was established. In intercropping, maize hybrid RAGT Zanetikks with soybean varieties Sirelia and Sakuza resulted in significant increases in maize yield across all fertiliser treatments and the control variant, indicating additional nitrogen supply to the maize through nitrogen fixation by soybeans (Table 8).

Table 8. Yield of monoculture and intercropped maize and soybean, t/ha, 2022-2024

Hybrid + Variety	Yield, t/ha								
	M	S	M+S	M	S	M+S	M	S	M+S
	Fertilisation, kg/ha a.s								
	No fertiliser (c)			$N_{60}P_{45}K_{45}$			$N_{90}P_{60}K_{60}$		
RAGT Zanetikks, (c)	7.21	–	7.21	9.32	–	9.32	10.26	–	10.26
Sirelia	–	2.24	2.24	–	3.32	3.32	–	2.78	2.78
Sakuza	–	2.55	2.55	–	3.47	3.47	–	2.64	2.64
RAGT Zanetikks + Sirelia	7.95	1.81	9.76	10.74	2.59	13.33	12.19	2.32	14.51
RAGT Zanetikks + Sakuza	8.02	1.95	9.97	10.92	2.73	13.65	12.24	2.46	14.70
LSD, t/ha	0.38	0.12	0.42	0.43	0.14	0.43	0.44	0.14	0.46
LSD for any means, t/ha		0.88							

Note: M – maize; S – soybean; M+S – maize and soybean together, a.s. – active substance, c – control
Source: compiled by the authors

The yield increase of maize in intercropped systems, compared to monoculture, was 0.74-0.81 t/ha (10.3-11.2%) in the variant without fertiliser application; 1.42-1.60 t/ha (15.2-17.2%) with the application of $N_{60}P_{45}K_{45}$; 1.93-1.98 t/ha (18.8-19.3) with the application of $N_{90}P_{60}K_{60}$. At the same time, the yield of soybean varieties in intercropped systems decreased compared to monoculture.

DISCUSSION

Innovative approaches to maize and soybean cultivation technologies are taking their production to a new level of economic, agricultural, and environmental efficiency. Intercropping of legumes and cereals has several advantages for partner crops, but at the same time, several questions require further research. In modern intensive production, intercropping is of great importance for many agricultural production systems, which is based on self-sufficiency of crops in nutrients under resource-limited conditions. The agroecological practice of intercropping, which involves growing two or more crop species or genotypes together, while they coexist for a certain period of time, is now becoming widespread (Mthembu *et al.*, 2018; Allison, 2022).

In Ukraine, research on intercropping of cereals and legumes is insufficient and many questions remain unanswered. In this regard, an ongoing study was conducted in 2022-2024 in the Right-Bank Forest-Steppe region of Ukraine on typical chernozems with intercrops of maize and soybean.

According to the research of L. Feng *et al.* (2020), intercropping changes the coenotic relationships in the agrocenosis compared to monoculture agrocenoses of similar hybrids and varieties, which is manifested in several biological and morphological features of crop development and the formation of their productivity. In the current study, a change in the duration of the growing period of crops was also established depending on mono- or two-component sowing, combinations of soybean varieties with a maize hybrid, and the influence of nutrition on the rate of passage of the growing period. An increase in the duration of the growing period of soybean varieties was established when sown in intercrops. Increasing fertiliser rates further prolongs the growing period. The range of variation in the duration of the growing period in the soybean variety Sirelia was 95114 days and in the variety Sakuza – 105-124 days; for the maize hybrid RAGT Zanetikks – 115-127 days. It should be taken into account that maize with FAO 320-350 in intercrops is advisable to grow with mid-season soybean varieties that require 2,300-2,400°C of active temperatures for crop ripening, which will ensure the correspondence of the development stages of partner crops and reduce interspecific competition.

Intensifying photosynthesis is one of the primary goals in agriculture, offering qualitatively new opportunities to increase crop yields. According to M. Baslam (2020), this issue must be addressed considering the trends of climate change on the planet, and the increasing concentration of CO_2 in the atmosphere, which can positively impact the productivity of C3-plant species, especially in arid regions and drought-prone areas. The current study revealed competition between crops in intercropping for vital factors in the first and second tiers of maize and the entire soybean plant. The hybrid RAGT Zanetikks has a clearly expressed erectophile leaf type, which contributes to reducing competition for vital factors and can be recommended for growing this hybrid in intercrops. The leaf surface area increased with increasing fertiliser rates: by 19.4% when growing the maize hybrid RAGT Zanetikks; 14.3% for the soybean variety Sirelia; 13.1% for the soybean variety Sakuza; 15.5% for intercropping RAGT Zanetikks + Sirelia; 16.5% for intercropping RAGT Zanetikks + Sakuza. W. Wang *et al.* (2022) also demonstrated that intercropping improves photosynthetic rate, instantaneous growth rate, water use efficiency for each species, and increases the land equivalent ratio. Photosynthetic potential characterises the intensity of photosynthesis and the accumulation of dry matter. The results of current research showed that the photosynthetic potential of crops for an individual culture was higher in monocultures, however, in total, it was higher in intercrops. With the application of fertilisers, photosynthetic potential increases and for the combination of RAGT Zanetikks + Sakuza it amounts to a total of 4.12 and 4.52 million m^2*days/ha and, in particular, for maize, the indicator corresponds to the potential in monocultures. Intercropping maize with legumes, unlike monocultures, uses natural resources more efficiently, especially light, since the stems and leaves of cereals and legumes located at different tiers ensure fuller utilisation of solar energy. Light intake by legumes can be improved by choosing the appropriate plant type and its architecture, in connection with which research on creating a crop with a certain selection of crops and their placement is extremely important. Studies by W. Wang *et al.* (2022) have shown that intercropping cereals with legumes contributes to a greater accumulation of dry matter and an increase in grain yield compared to monoculture, including due to photosynthetic activity.

Sufficient soil nitrogen content is essential for optimal plant growth and development, making it a key indicator of soil fertility. One of the primary benefits of intercropping maize with legumes is the additional nitrogen supply to maize plants through nitrogen fixation by legumes. One of the earliest studies by R.W. Willey (1979) revealed that legumes grown between crops can provide an additional 40 kg/ha of nitrogen for maize yield formation. Thus, legumes are a stable source of nitrogen in cereal-legume cropping systems. K. Fujita *et al.* (1992) demonstrated the mechanism of biological nitrogen fixation in intercrops of cereals and legumes. The transfer of nitrogen from legumes to cereals increases system yield and its use efficiency. The introduction of nitrate-tolerant legumes, whose biological nitrogen fixation is believed to be minimally affected by the application of combined N, can increase the amount of N available to the cereal component (Moshira *et al.*, 2014; Zhang *et al.*, 2014).

In this study, the content of nitrate nitrogen in the soil varied depending on the cultivation of mono- and intercrops of maize and soybeans, and fertilisation. At the maize tasselling stage, the highest reserves of nitrate nitrogen were observed in monocultures of soybeans. In intercrops, its content was lower, which is associated with significant nitrogen uptake by maize plants. When growing intercrops of maize with soybeans, the content of nitrate nitrogen in the soil of the control variant was lower – 14.5-14.7 mg/kg of soil. The content of nitrate nitrogen in the soil when growing maize in a monoculture was 12.1 mg/kg of soil.

Under conditions of limited nitrogen availability, biological nitrogen fixation is the primary source of nitrogen in mixed legume-cereal systems (Adeleke & Haruna, 2012). Patterns of soil nitrogen use by intercrops depend on the nitrogen source and legume species. The efficiency of nitrogen use by crops in intercropping depends on their correct selection. Thus, in the studies of A. Wysokiński & B. Kuziemska (2019), it was shown that under conditions of intercropping at a low background of nitrogen fertilisers (30 kg/ha), regardless of the proportion in the sown seed mixture, the main source of nitrogen for lupin was the atmosphere and soil reserves – 65.2% in total nitrogen uptake, and for triticale – 68.8%.

The intercropping of legumes and maize, as explored by M. Dahmardeh *et al*. (2010) and J. Nasar *et al*. (2020), results in higher overall yields compared to growing either crop individually. With an ideal population ratio, intercropping can yield greater gross returns. The current study confirms that maize responds positively to increasing fertiliser rates. With the application of $N_{90}P_{60}K_{60}$, higher maize yields were obtained, both in monocultures and intercrops. In monoculture, maize yield was 10.26 t/ha, while in intercropping maize RAGT Zanetikks and soybean Sakuza – 12.24 t/ha. The surplus yield of maize in intercrops was 1.98 t/ha (16%). Calculations of nitrogen removal by the maize yield increase indicate the use of additional nitrogen by maize at a level of about 53.7 kg/ha. The gross yield in intercropping for this combination was 14.7 t/ha. With the application of $N_{60}P_{45}K_{45}$, maize yield was 9.32 t/ha in monoculture and 10.92 t/ha when intercropping the maize hybrid RAGT Zanetikks and soybean variety Sakuza. The gross yield in intercropping when sowing this combination of hybrid and variety was 13.65 t/ha.

There is a positive correlation between crop diversity and productivity. Numerous studies have been conducted on intercropping in irrigated areas and regions with abundant rainfall (Tsubo *et al.*, 2005; Hassan, 2014). However, as highlighted by W. Wang *et al.* (2024), there is a significant lack of research in semi-arid regions, despite the urgent need for ecological approaches to enhance crop yields and water use efficiency in such conditions.

For soybeans, it was established that the increase in yield in monoculture occurred with the application of $N_{60}P_{45}K_{45}$, compared to the control variant and with the application of $N_{90}P_{60}K_{60}$. The yield increased by 35.1% and 48.2% for the Sirelia and Sakuza varieties, respectively. With the application of $N_{90}P_{60}K_{60}$, the yield decreased. However, in intercrops, while the soybean yield decreased in the control variant compared to monoculture, the yield increased with an increase in the fertiliser application rate, which may indicate the joint use and redistribution of nutrients between crops. The current study also established a positive effect of the interaction of intercropping maize and soybeans. Calculations of nitrogen removal by the increase in maize yield indicate the use of additional nitrogen by maize at a level of about 53.7 kg/ha.

During 2022-2024, the current study established that the highest efficiency of microbiological processes occurred with the application of $N_{60}P_{45}K_{45}$. Thus, in monocultures of maize and soybeans, the biological activity of the soil was 39.4 and 47.2 mg CO_2/kg soil/day, respectively, indicating more intensive respiration under soybean crops. In mixed crops, an increase in this indicator was observed, which is associated, in addition to the symbiotic ability of soybeans, also with a welldeveloped root system of maize, and as a result, an increase in the coefficients of the utilisation of mineral nutrients. It should be noted that the higher biological activity of the soil in mixed crops is due to its temperature regime. The maize hybrid has an erect leaf arrangement, which at high air temperatures contributes to an increase in soil temperature, leading to unproductive water losses and impaired nitrogen uptake. Studies have established that the availability of nitrogen from the soil depends on its temperature. If the soil temperature is 20-25°C, then the sequence of nutrient consumption by plants is as follows: nitrogen-phosphorus-potassium. With an increase in temperature to 28°C and above, the sequence changes as follows: phosphorus-potassium-nitrogen. Current studies have established that the difference between the soil temperature in the rows of monocultures and mixed crops was 8-10°C in favour of the former. Therefore, due to the decrease in soil temperature in mixed crops, soil-forming microbiological processes proceeded more intensively, nitrogen consumption by plants was better, and, accordingly, a higher overall biological activity of the soil was recorded.

CONCLUSIONS

Intercropping of maize and soybeans has significant potential for expansion due to the efficient use of environmental factors. Photosynthetic activity of crops and yield are closely correlated (r=0.93-0.99). The leaf area of maize and soybean crops individually is formed larger in monocultures; in intercrops of maize and soybeans, a decrease in the leaf area of individual components was noted, but the total leaf area of the intercrop increased compared to monocultures. With the application of increasing fertiliser rates, the leaf area increased in monocultures and intercrops by 13.1-19.4%.

The photosynthetic potential of crops characterises the intensity of photosynthesis and the effective accumulation of dry matter. The photosynthetic potential of intercrops RAGT Zanetikks + Sakuza is 2.96 million m^2*days/ha, indicating a high positive interaction of crops in the accumulation of dry matter per unit of leaf area.

The content of nitrate nitrogen in the soil was higher in soybean monocultures – 14.9-15.1 mg/kg of soil; maize – 10.4-13.2 mg/kg; in intercrops of maize and soybeans, a decrease in its content was recorded, which is due to the additional use of nitrogen by maize – 12.1-14.1 mg/kg. The effectiveness of microbiological processes varies depending on the rates of fertiliser application and the composition of crops. Soil biological activity was higher with the application of $N_{60}P_{45}K_{45}$ in maize and soybean monocultures – 39.4 and 47.2 mg CO_2/kg soil/day, respectively. In intercrops, an increase in soil biological activity was observed up to 52.6-55.1 mg CO_2/kg, which confirms the positive interaction of maize and soybeans.

An integral indicator of crop cultivation efficiency is their yield. When intercropping maize RAGT Zanetikks with soybean varieties Sirelia and Sakuza, significant increases in maize yield were obtained on all fertiliser backgrounds and without fertilisers, indicating additional nutrition for maize due to nitrogen fixation by soybeans. The increase in maize yield in intercrops, compared to monoculture, was 10.3-19.3% depending on the fertiliser rate. The highest maize yield was formed with the application of $N_{90}P_{60}K_{60}$: in monoculture – 10.26 t/ha; in intercropping – 12.19-12.24 t/ha. Soybean yield increased by 35.1% and 48.2% for the Sirelia and Sakuza varieties, respectively, with the application of a lower fertiliser rate – $N_{60}P_{45}K_{45}$. The gross yield in intercrops reached 14.5114.70 t/ha against the background of $N_{90}P_{60}K_{60}$.

The perspective for further research lies in the need for interdisciplinary studies to establish the mechanisms of interaction of all structural components of the agroecosystem formed by intercropping and the management of processes of agroecosystem productivity formation, microbiological studies of the soil, which can explain the mechanisms of interaction of the root system of two species in the plane of symbiotic fixation and the use of nutrients.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Ефективність міжвидових посівів в Лісостепу України

Анотація. Сумісні міжвидові посіви сільськогосподарських культур є важливим технологічним рішенням, яке забезпечує збереження ресурсів, підвищення валової урожайності культур, що є актуальним для забезпечення продовольчої безпеки людства. Метою дослідження було встановлення ефективності сумісних, міжвидових посівів кукурудзи та сої. При проведені досліджень були використані наукові методи проведення польових та лабораторних досліджень. Результати експериментальних досліджень були статистично обраховані та інтерпретовані. Встановлено, що міжвидові посіви кукурудзи ‹РЖТ Занетіккс' з сортами сої 'Сірелія' і 'Сакуза' мають низку переваг порівняно з одновидовими посівами і в першу чергу щодо формування урожайності. Кукурудза досить ефективно використовувала додатковий азот ґрунту фіксований соєю в сумісних посівах – отримано суттєві прирости урожайності кукурудзи на всіх фонах добрив і без добрив. Приріст урожайності кукурудзи в сумісних посівах, порівняно з одновидовим посівом, склав 10,3-19,3 % залежно від норми добрив. Найбільша врожайність кукурудзи формувалася при внесенні $N_{90}P_{60}K_{60}$: в одновидовому посіві – 10,26 т/га; сумісному посіві – 12,19-12,24 т/га. Урожайність сої в сумісних посівах знижується, однак валова урожайність двох культур в сумісних посівах суттєво зростає і сягає 14,51-14,70 т/га на фоні $N_{90}P_{60}K_{60}$. Урожайність тісно корелює з площею листкової поверхні посівів (r = 0,93-0,99). Вміст нітратного азоту в ґрунті був вищим під соєю, однак знижувався під міжвидовими посівами. Біологічна активність ґрунту зростала за внесення $N_{60}P_{45}K_{45}$ в одновидових посівах кукурудзи і сої – 39,4 і 47,2 мг CO_2/кг ґрунту/добу; сумісних посівах – 52,6-55,1 мг CO_2/кг ґрунту/добу. Результати досліджень мають значне практичне значення для виробництва з огляду на ресурсозбереження та зростання валового виробництва зерна

Ключові слова: площа листкової поверхні; фотосинтетичний потенціал; біологічна активність ґрунту; вміст нітратного азоту в ґрунті; урожайність